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NO. MS PR 61-62

Project No. 02551

CONTRACT NO. DA-04-200-507-ORD-333
UNDER ARMY PROJECT NOS. 593-32-003 AND 593-32-005
FINAL SUMMARY REPORT
STUDY IN WELDING HIGH STRENGTH ALUMINUM ALLOYS AND
STUDY OF EFFECT OF ALLOY COMPOSITIONS AND TEMPER AS
WELL AS INGOT QUALITY AND PLATE QUALITY ON THE
WELDABILITY, MECHANICAL AND BALLISTIC PROPERTIES OF
MEDIUM AND HIGH STRENGTH ALUMINUM BASE ARMOR

J. B. Hess

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October 17, 1961
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By

J. B. Hess

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2. Welding - Aluminum alloys.
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INTRODUCTION

Before this study began, the U. S. Army had developed new concepts of mobile striking forces that could be used for the rapid envelopment of strategic enemy strong points. These concepts entailed plans for using new types of vehicles, including armored personnel carriers that could be air-borne and air-dropped. If an occasion for use of these mobile forces arose, men, equipment and vehicles would be parachuted onto lightly defended terrain near a critical target. They would then advance across country and over streams to attack the target with the greatest possible speed (Ref 1).

The choice of armor material for such air-droppable vehicles requires careful consideration of a number of factors in addition to ballistic performance. These criteria have been discussed elsewhere (Ref 1). For the present purpose, it is sufficient to note that (1) a high degree of ballistic protection per unit weight and (2) adequate weldability rank very high on the list of essential characteristics.

In Ordnance tests preceding the present contract, aluminum alloy 2024-T4 plate had shown capabilities for resisting ballistic penetrations by armor piercing projectiles and fragments to a degree which compared favorably with conventional steel armor of equal weight. The principal drawback preventing utilization of 2024-T4 alloy for the desired armor application was its welding characteristics.

This alloy could not be satisfactorily welded when the areas to be joined were under structural constraint. Furthermore, multipass MIG welds of high weld quality could not be obtained consistently even in unrestrained joints, and relatively poor joint efficiencies and low transverse weld ductilities resulted.

In studies conducted prior to the present contract, Kaiser Aluminum & Chemical Corporation's Department of Metallurgical Research had added chlorine, aluminum chloride and other halides to the protective gas surrounding the welding arc in an effort to reduce weld metal porosity^x. Substantial improvements in weld quality and transverse weld properties had thereby been produced in weldments in 1/4" thick 5083-H113 plate, using a square butt joint design with both one and two welding passes and with both 5083 and 5056 filler wires. Furthermore, three promising methods of introducing the halogen or halide additions to the welding arc area had been demonstrated.

Recognizing the importance of the above welding techniques as potential methods for obtaining improved weldability and better weld quality in the welding of other high strength aluminum alloys, the Frankford Arsenal arranged for sponsorship of additional studies. The broad original objective of these studies was to develop improved techniques for welding high strength aluminum alloys so that satisfactory welded plate samples (representing severely constrained weld joints, as in the Ordnance H-plate Test) could be produced in one or more of the strong aluminum alloys for evaluation as weldable military armor.

The investigation conducted by this laboratory under the terms of the resulting Contract No. DA-04-200-507-ORD-333^{xx} and its nineteen subsequent modifications during the period August 1, 1954, through January 31, 1961, were logically divided into a series of different studies, or phases. These different phases resulted as a natural consequence of interim modifications and extensions of the original objectives as the project progressed and experimental results and conclusions were developed. In all, a total of thirteen major phases of generally related investigations were

^x These techniques are protected by patent rights of the Kaiser Aluminum & Chemical Corporation.

^{xx} Originally designated Contract No. DA-04-200-ORD-333.

carried out to their logical conclusions under this contract. A detailed technical report (Phase Report) on each of these thirteen phases has been issued (Refs 2-14) and is on record. Since this series of Phase Reports already provides the complete technical details of the experimental studies and their results, the principal purpose of this Summary Report will be to show the relationship and continuity of the separately reported phases, and to provide a general synopsis of the entire project.

HISTORY OF THE PROJECT

Development of Welding Techniques for High Strength Aluminum Alloys

As mentioned previously, the first goal of this project was to develop improved techniques for welding high strength aluminum alloys in relatively thick sections so that welded plate samples having severely constrained joints, as in H-plates, could be produced in one or more of the strong alloys for evaluation as possible light-weight weldable armor material. Phases 1 through 4 were specifically concerned with this objective.

In Phase 1 (Ref 2), the emphasis was placed on developing welding procedures to reduce weld metal porosity and other unsoundness in multipass MIG weldments in 5083-H113 and 2024-T4 alloy plates. For this purpose, the effects of halogen and halide additions to the welding arc area were investigated in considerably greater detail than in our studies which preceded this contract.

The halogen and halide additions were found to be particularly effective in reducing the amount of coarse porosity and entrained dross in multipass 5083 welds. Due to the improved weld metal soundness, the mechanical properties of such weldments were substantially increased. The improvement effected in transverse weld ductility was especially noteworthy.

It was also determined that the MIG- Cl_2 welding technique produced substantial improvements in the radiographic and macrosection soundness ratings of 2024-T4 alloy multipass weldments. However, with this alloy, the improved weld metal quality did not produce correspondingly impressive improvements in the mechanical properties of the weldments, and the elongation, in particular, remained discouragingly low.

In Phase 2 (Ref 3), the objective was to develop improved filler alloys which would produce increased weld strength and higher joint efficiencies in 5083-H113, 2024-T4 and 7075-T6 weldments. The studies were restricted to the TIG welding process in this phase.

Experimental filler alloys were developed which produced deposited weld metal of higher tensile strength in the as-welded condition than the minimum strength available in the weld-heat-affected-zones of each base plate alloy. However, this higher strength weld metal did not improve the transverse weld strengths, or joint efficiencies, of 2024-T4 or 7075-T6 weldments. The low ductilities and mediocre strengths of weldments in both of these alloys were shown to be due to a narrow zone of eutectic melting which was created by the welding heat in the heat-affected-zones of the base plates directly adjacent to the weld metal beads. Severe microfissuring frequently occurred in these zones of eutectic melting and in the weld metal itself, thereby causing the erratic weld strengths and impaired ductilities characteristic of 2024-T4 and 7075-T6 weldments. In contrast, no damage from eutectic melting was observed in 5083 alloy weldments.

Fourteen experimental filler alloy compositions were found to produce weld metal of sufficient strength in 5083-H113 alloy TIG weldments so that the point of failure, in transverse weld tensile tests, was shifted from the weld metal to the heat-affected-zone of the parent plate. These welds exhibited high joint efficiencies and excellent ductilities. Weld-cracking-sensitivity tests indicated that the experimental fillers had good resistance to hot cracking. It was also demonstrated by statistical studies that use of the experimental fillers should result in a significant improvement in the reproducibility of the transverse weld properties of 5083 weldments.

Many of the most promising high strength experimental filler alloys contained zinc. Since there was a possibility that 5083 weldments might be susceptible to stress corrosion cracking if zinc-containing filler alloys were used, this possibility was carefully explored in Phase 3 (Ref 4).

Accelerated laboratory tests and natural environment exposure tests were carried out in investigating this possibility.

The corrosion tests demonstrated that 5083 TIG weldments made with zinc-containing filler alloys are highly susceptible to stress corrosion cracking and to galvanic corrosion of the weld metal. The degree of susceptibility appeared to increase with increasing zinc content, or with increasing total content of zinc plus magnesium, in the filler alloys. However, it was also found that 5083 weldments produced with a zinc-free Al-Mg-Mn type alloy filler are not susceptible to either galvanic corrosion or stress corrosion. Furthermore, in this study, the zinc-free filler composition produced 5083 TIG weldments of essentially the same strength as the experimental zinc-containing filler alloys.

Concurrently with these corrosion tests, the filler alloy development studies were extended, in Phase 4 (Ref 5), to the MIG welding process. For this study, MIG filler wire was produced experimentally in nine Al-Mg-Mn, Al-Zn-Mn, and Al-Mg-Zn-Mn type compositions, including those which had shown promise in the preceding TIG welding studies (Ref 3). These filler alloys were then evaluated by producing both single-pass and multipass weldments in 5083-H113 base plate.

It was found that all nine of the experimental fillers produced 5083 MIG weldments of higher tensile strength than could be obtained with the 5083 or 5356 filler alloys conventional at that time. However, those filler alloys which contained zinc showed an undesirable tendency to develop brittle, grain-boundary network structures in the underlying beads of multipass welds, due to the reheating these beads received during subsequent overlaying passes. Because of this embrittling effect, and also because of the stress corrosion susceptibility of these weldments which was demonstrated concurrently in Phase 3 (Ref 4), further investigation of the use of zinc-containing filler alloy compositions for the welding of 5083 alloy was abandoned. On the other hand, it was

again demonstrated in this study that a zinc-free filler alloy of the Al-Mg-Mn type, but containing more magnesium and manganese than the 5083 and 5356 conventional filler alloys, produced ductile 5083 weldments with transverse weld strengths essentially equal to those achieved with the zinc-containing filler compositions.

Evaluation of 5086 and 5083 Alloys as Candidate Armor Materials

It had been originally assumed that a heat treatable aluminum alloy, such as 2024 or 7075, would probably be required in order to achieve ballistic protection capabilities comparable to conventional steel armor of equal areal density. However, the preceding phases of this contract had failed to disclose any promising methods for circumventing the poor weldabilities of these alloys so as to make them adaptable for welded armored vehicle construction. On the other hand, these studies had established that higher weld strength and appreciably greater weld ductility could be obtained with the Al-Mg-Mn type non-heat-treatable alloy 5083 than with the heat treatable 2024 and 7075 alloys. Accordingly, an investigation of the ballistic protection characteristics of the Al-Mg-Mn alloys appeared desirable, and the contract was modified, in June, 1956, to authorize an evaluation of two of these alloys, namely, 5086 and 5083.

The evaluation study had three parts. The first part involved an attempt to determine the temper condition which would produce best ballistic performance. Plates 1-1/4 inch thick were produced in three tempers, corresponding to three different degrees of strain hardening, in each of the two alloys. These sample plates were supplied to the Frankford Arsenal who then conducted the ballistic testing and evaluation. The second part consisted of determining the effect of plate thickness on the degree of ballistic protection obtained. For this purpose, sample plates were produced in 3/4 inch and 1-1/2 inch thicknesses in a temper corresponding to the maximum strain hardened temper furnished in the 1-1/4 inch thickness. Again, these sample plates were supplied to the Frankford Arsenal who carried out the ballistic testing and evaluation.

The third part of this study consisted of developing preferred welding practices, and then producing 1-1/4 inch thick H-plates from each alloy in the maximum temper condition. This work was carried out in Phase 5 (Ref 6). H-plates with satisfactory weld quality were produced in both alloys without significant difficulties. The completed H-plates were sent to the Frankford Arsenal who then carried out the ballistic tests and evaluated the performances of the weldments.

It was reported (Ref 15) that the ballistic test performances of the 5086 experimental armor plates were considered inadequate. However, the protection provided by the 5083 plates was rated as encouragingly good. The H-plates also reportedly exhibited satisfactory shock performance in the ballistic tests conducted.

Evaluation of 5083-H115, MR19, MR20 and 6066-T6 Alloys

Even though the ballistic performance of 5083-H113 had been considered promising in the above tests, still better performance was desired. Accordingly, further studies were authorized in May 1957, to determine if ballistic protection ratings superior to that of 5083-H113 plate could be achieved either with 5083 alloy in a specially-produced temper of higher yield strength than the -H113 temper or with other experimental weldable alloys of similarly higher yield strengths.

Experimental armor plate samples were accordingly produced in a series of three increasingly strain hardened temper conditions of 5083 alloy, including one temper (-H115) wherein the degree of strain hardening was approximately twice that of the previously tested -H113 temper. In addition, armor samples were also produced in the experimental plate alloys MR19, MR20 and 6066-T6 for reasons which have already been discussed (Ref 7). As in the preceding program, these armor samples were supplied to the Frankford Arsenal who conducted the actual firing tests and evaluated the ballistic performances.

This laboratory carried out an associated investigation of the weldabilities of these alloys as Phase 6 (Ref 7) of the contract. In this study, we attempted to fabricate H-plates from each of the alloys^x, using the temper condition which, in each case, had produced the best ballistic protection rating. Alloy 6066-T6 was found to be too crack-sensitive with either 5556 or 4043 alloy filler to permit the constrained cross-bar joint of the H-plate to be fabricated without cracking. However, the 5083-H115 and MR19 alloys both showed adequate weldabilities to permit fabrication of sound H-plates without unusual welding techniques.

In the Frankford Arsenal's ballistic tests, the MR20 alloy showed a severe spalling tendency, and MR19 exhibited a slight tendency to spall while the 5083-H115 plate of essentially equal yield strength showed no spalling tendency whatsoever. Possible causes of these respective spalling tendencies were investigated in Phase 7 (Ref 8). It was found that the spalling tendencies of the MR20 and MR19 samples were probably due to the grain boundary type precipitation which occurred in those alloys.

Effect of Weld Quality on Ballistic Performance of 5083 Alloy Weldments

In the preceding program, 5083-H115 aluminum armor had shown ballistic protection performances sufficiently equivalent to conventional steel armor, on an equal weight basis that Ordnance decided to produce several prototype aluminum-armored units of the T113 personnel carrier. These prototype units were to be tested in comparison to equivalent vehicles constructed from conventional steel armor plate.

It was expected that a very high order of weld quality might be required in the weldments of these aluminum vehicles so as not to jeopardize their mechanical and ballistic performances. Accordingly, the Frankford Arsenal requested development of sensitive techniques for inspecting these weldments radiographically. This was done in Phase 8 (Ref 9).

^x MR20 was not included in this program because the Frankford Arsenal's ballistic tests had meanwhile indicated that this alloy exhibited a severe spalling tendency and was considered relatively unpromising as an armor material on this account.

An additional part of Phase 8 (Ref 9) involved evaluating the weld quality present in some typical welded joints produced by the vehicle manufacturer. This was to be followed by ballistic testing of the weldments in order to determine the level of weld quality actually needed for satisfactory service behavior. Unfortunately, the quality of these sample weldments was found to be too erratic to permit obtaining significant ballistic test results, so that another approach to the problem of establishing adequate standards for weld quality had to be taken.

In Phase 9 (Ref 10), a different approach was utilized. A series of weldments containing controlled types of weld defects in controlled amounts was produced by specialized welding techniques. Then, these welded samples were carefully evaluated by nondestructive inspection methods, supplemented in several instances by destructive examinations, in order to establish the actual levels of weld quality present. Finally, the weldments were shock tested by a ballistic method at the Frankford Arsenal, and the resulting weld damage was correlated with the defect types and concentrations. This study showed that the weld defects affected the ballistic performance of the weldments, but not to an alarming degree. In no case was brittle, catastrophic failure of the aluminum weldments observed, even when weld defects were of such severity as to be unacceptable under virtually all commonplace standards of weld quality.

Additional Attempts to Develop Aluminum Armor with Improved Ballistic Characteristics

The aluminum T113 prototypes had meanwhile been built and tested. Their performance proved to be sufficiently advantageous in comparison to similar steel-armored vehicles that aluminum armor was specified for the subsequent M113 production models. This acceptance of the aluminum armor did not signify, however, that all problems associated with aluminum armor development and utilization had been successfully solved. On the contrary, it was reported (Ref 15) that different production lots of 5083-H115 armor plate showed substantial variations in ballistic

protection ratings^x and that the margin of overall advantage as compared to steel armor was fairly small. Accordingly, further studies to develop better aluminum armor alloys seemed advisable; and three investigations, all broadly directed toward this objective, were undertaken concurrently as Phase 10, 11 and 12.

In Phase 10 (Ref 11), an attempt was made to determine the cause of the variations in ballistic performance of different lots of 5083-H115 armor plate observed in the 45° obliquity ballistic test with 20 mm FS projectiles. Samples from one lot which failed the ballistic test were carefully compared with corresponding samples from two lots which successfully passed the test. The examinations included comparisons of the chemical compositions, mechanical properties, macrostructural and microstructural characteristics, lattice parameters, hardness variation patterns throughout the plates, and residual stress patterns. The only difference of apparent significance that could be found between the acceptable and unacceptable lots was a minor microstructural variation: the unacceptable lot contained a precipitate of platelet-type particles which was substantially absent from the acceptable lots. Methods of controlling this microstructural feature were developed, and experimental plates were produced with and without the platelet precipitate present. Ballistic tests of these plates then showed, however, that the presence or absence of this particular microconstituent had no consequential effect on the ballistic performance of 5083-H115 armor.

The purpose of Phase 11 (Ref 12) was to determine if the ballistic performance of the work-hardenable Al-Mg-Mn type alloys could be improved by increasing the magnesium alloying content so as to raise the yield strength of the armor plate. Investigation of an alloy containing nominally 7% Mg was specifically requested. The first part of this study consisted of (1) determining which of several logical variations of a nominal Al-7% Mg type composition might have the greatest promise as an armor plate material, and then (2) developing appropriate processing practices for the alloy selected. On the basis of the preliminary tests, a nominal alloy composition of 0.15% Si,

^x The ratings of ballistic merit were principally derived by determining the V50 PBL (Protection Ballistic Limit) at 45° striking obliquity with 20 mm fragment simulator projectiles. At a later date, the 45° obliquity firing was replaced by 0° obliquity firing tests because it was found that the 45° obliquity ballistic tests yielded non-reproducible results with fragment simulator projectiles.

0.20% Fe, 0.40% Mn, 7.0% Mg and 0.13% Cr (Alloy MR21) was selected for more extensive evaluation. A mill ingot of this composition was cast and processed to 1-1/4 inch thick plates of various tempers. These plates were ballistically tested by Frankford Arsenal using 20 mm fragment simulator projectiles at 45° striking obliquity. These tests showed that the ballistic protection ratings of the experimental MR21 alloy were not superior to those obtainable with 5083.

Phase 12 (Ref 13) was devoted to an attempt to develop a simple mechanical test for armor plate that would give test results correlating directly with the results of actual firing tests. A satisfactory test of this type would be useful for several purposes, namely: (1) to reduce, or possibly eliminate, the need for actual firing tests in evaluating the ballistic performance of full-scale samples of armor plate; (2) to provide a method for obtaining preliminary estimates of the possible merits of candidate armor alloys or special fabrication practices from small-scale laboratory specimens; and (3) possibly to reveal new knowledge about the structural mechanisms of ballistic penetrations and the metallurgical factors governing ballistic behavior which might indicate principles that could be utilized directly in developing armor with improved ballistic properties. In the experimental test procedure, a hardened steel punch with a nose shape approximating the ogive of a .30 cal AP M2 projectile tip was pushed through the thickness of a plate sample to determine the maximum load required for complete penetration of the punch. Unfortunately, the punch test ultimate loads showed no useful degree of correlation with firing test results on the same plates; hence, the test was abandoned.

Effect of Ingot Quality and Plate Quality on Ballistic Performance of 5083-H115 Armor Plate

From practically the beginning of this project, it had been intuitively expected that ballistic performance might be affected adversely if the armor plate contained unhealed porosity, inclusions, laminations, or other plate defects. Such plate defects can result from unsoundness present in the original ingots.

Phase 13 (Ref 14) was undertaken for the purpose of obtaining quantitative information about the effect of such defects on the ballistic behavior of plate so that standards could be established which would define the quality levels necessary in plate and/or ingot to avoid significant impairment of ballistic performance. For this study, a series of 5083 ingots was produced by specialized techniques of molten metal treatment and casting practices to produce ingots with controlled types and concentrations of ingot defects^x. Ingot of highest obtainable quality were also produced. Ten of these ingots, selected on the basis of ultrasonic tests, vacuum freeze tests and dye penetrant tests to represent a wide range of variation in ingot quality, were then rolled to 1-1/4 inch thick -H115 temper armor plates.

When the quality of the resulting plates was evaluated ultrasonically, it was found that all plates contained large areas which were rated as "sound", ie, free of any specific defects detectible by the sensitive ultrasonic technique utilized. A few plates also contained "unsound" areas where defects existed in substantial concentrations throughout areas of appreciable size. Ballistic tests (using 20 mm FS projectiles, 0° obliquity) were conducted on the "sound" areas of 19 plates, and on the "unsound" areas available in 5 plates. In addition, a number of isolated defects in certain of the plates were tested to the best extent possible by utilizing single-round firings. The results from these tests on limited samples failed to show any rational relationship between ballistic properties and the presence of defects as measured by ultrasonic techniques over a substantial range of ultrasonic quality levels from "no defect" to a defect size greater than that in No. 8 Alcoa block.

RESULTS AND CONCLUSIONS

Full details of the investigations summarized above are already on record in the individual Phase Reports (Refs 2-14). These should be consulted for information about the specific results, discussions, and conclusions.

^x The specialized techniques utilized for this purpose were developed entirely at the expense of Kaiser Aluminum & Chemical Corporation. In addition, the casting of some 40 ingots and the subsequent production of plate from 10 of these ingots was also performed without cost to the government in furtherance of this project.

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The many employees of Kaiser Aluminum & Chemical Corporation who contributed directly to the conduct and results of these studies are too numerous to credit individually. Kaiser Aluminum assumed the expense of casting mill-size ingots and producing plate by special fabrication practices to provide the desired ballistic samples needed in a number of the individual phases of this project. Without this contribution, many of the studies could not have been successfully completed.

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